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A COMPARATIVE EVALUATION OF HOCKEY HELMETS ON THE BASIS
OF SELECTED IMPACT MEASUREMENTS

by



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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled A Comparative Evaluation of Hockey Helmets on the Basis of Selected Impact Measurements submitted by Valkmar Erich Schneider in partial fulfilment of the requirements for the degree of Master of Arts.

ABSTRACT

The purpose of the study was to provide a comparative evaluation of the energy absorbing qualities of commercial hockey helmets. The front and back positions of ten different hockey helmets were subjected to standardized blows from a pendulum impact arrangement. The helmets were fitted onto a wooden headform weighing 9.2 pounds and suspended from the ceiling by two steel cables. A piezoelectric accelerometer mounted in the headform at a point opposite the point of impact was employed to detect impact effects. The accelerometer's voltage output was amplified and imposed on the screen of a storage oscilloscope. The resultant tracings took the form of acceleration-time curves and were photographed for permanent records. Two parameters, peak acceleration and kinetic energy, were calculated from the photographed recordings and used to evaluate the hockey helmets.

A significant difference between the energy absorbing qualities of the ten helmets was found to exist. Helmets varied according to the position tested and the velocity of the blow. On the whole, no significant difference was found between the front and back positions. In general, the helmet that developed the lowest order of acceleration and dissipated the resultant energy over a broad base in terms of time was one that was constructed out of a rigid shell and utilized a suspension system similar to that found in a football helmet.

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TABLE OF CONTENTS

CHAPTER		PAGE
I.	STATEMENT OF THE PROBLEM	1
	Introduction	
	The Problem	
	Definition of Terms	
	Delimitations	
	Limitations	
II.	RELATED LITERATURE	6
	Medical Aspects of Head Injury	
	Impact Studies Conducted on Dogs and	
	Human Cadavers	
	Impact Studies Conducted on Various	
	Types of Headforms	
	Impact Studies Conducted on Human Beings	
	Summary of Related Literature	
III.	METHODS AND PROCEDURES	24
	Experimental Apparatus	
	Experimental Procedure	
IV.	ANALYSIS AND RESULTS	34
	Peak Acceleration	
	Kinetic Energy	
	Comparing Results for Peak Acceleration	
	and Kinetic Energy	
	Statistical Analysis	

CHAPTER	PAGE
V. SUMMARY AND CONCLUSIONS	51
Summary	
Conclusions	
BIBLIOGRAPHY	53
APPENDIX A: Hockey Helmets Used	56
APPENDIX B: Various Wave-forms	61
APPENDIX C: Formulas	65

LIST OF TABLES

TABLE		PAGE
I.	Rankings of Helmets on the Basis of Peak Acceleration in g Units for Three Release Heights of the Pendulum at the Front Position	36
II.	Rankings of Helmets on the Basis of Peak Acceleration in g Units for Three Release Heights of the Pendulum at the Back Position	37
III.	Rankings of Helmets on the Basis of Velocity Squared in Inches Per Second for Three Release Heights of the Pendulum at the Front Position	43
IV.	Rankings of Helmets on the Basis of Velocity Squared in Inches Per Second for Three Release Heights of the Pendulum at the Back Position	44
V.	Analysis of Variance-Summary Peak G's for all Blows	49

LIST OF FIGURES

FIGURE		PAGE
1.	Side View of Pendulum Impact Arrangement	25
2.	Flat Section of a Hockey Stick Shaft	26
3.	Electro-Magnetic Release Mechanism	26
4.	Centered Pendulum and Headform	28
5.	Side View of Headform with Inserted Bolt for Accelerometer Attachment	29
6.	Recording Instruments	31
7.	Test Set-Up Showing Oscilloscope with Camera Attachment	32
8.	The Effect of Three Release Heights of the Pendulum on Peak Acceleration for Ten Helmets at the Front Position	38
9.	The Effect of Three Release Heights of the Pendulum on Peak Acceleration for Ten Helmets at the Back Position	40
10.	The Effect of Three Release Heights of the Pendulum on Velocity Squared for Ten Helmets at the Front Position	46
11.	The Effect of Three Release Heights of the Pendulum on Velocity Squared for Ten Helmets at the Back Position	47

CHAPTER I

STATEMENT OF THE PROBLEM

Introduction

Protective equipment in athletics represents what is thought to be the best compromise between operational suitability and protective qualities. The athlete's protective equipment is designed to shield him from injury, but "must not interfere with his speed or agility, and its weight and bulk must not tax his energy or cause chafing or restriction of movement" (1:199). Various energies and resources are constantly being utilized to continually improve the design and basic construction of protective equipment.

Ice hockey is considered to be a body contact sport. Participants wear protective equipment to avoid possible injury. Hockey players, however, often neglect to protect the most important and perhaps most vulnerable part of their body - the head. Direct blows by a stick and puck, or falls and collisions, are the usual causes of head injury but most of the injuries are of a minor type (2, 3, 4). However, possible severe consequences of head injuries necessitates adequate protection even though incidence of head injuries is low.

The most common types of head injuries hockey players receive are lacerations and contusions to the scalp, skull fractures, and at the extreme, brain concussions that could result in permanent brain damage (3).

The hockey puck, which is employed to score goals as well as control the game, can be a potential hazard. A puck is a round disk measuring three inches in diameter and one inch in thickness. It is

constructed from processed rubber and weighs six ounces. A puck, when propelled by a hockey stick, is capable of travelling at speeds exceeding 110 miles per hour (5). By virtue of its small size and high velocity, a hockey puck is capable of producing severe injury. Campbell, Fournier, and Hill (6:923) provide further evidence that a hockey puck can be dangerous.

"Blow by hockey pucks have not been implicated previously, but we would defend our use of the term "puck aneurysm" as a means of drawing attention to a potentially serious hazard in an internationally popular sport. Although it is well known that to be struck on the head by a hockey puck cannot be an entirely benign event, it is perhaps insufficiently appreciated that a regulation hockey puck weighs 165 grams and may travel at a velocity in excess of 120 feet per second. When such a missile strikes the head, delayed as well as immediate sequela cannot be wholly unexpected. In the cases reported here, it may be felt that the patients got off lightly, but on the other hand, it can be pointed out that in both instances the injuries could have been prevented by the wearing of a suitably designed protective helmet."

Hockey sticks, when used in an erratic manner, intentionally or accidentally, are capable of inflicting minor to severe injuries to players. The recent death of a sixteen year old New Brunswick hockey player who was struck in the temporal area of the head provides evidence that a hockey stick can be potentially dangerous (7).

Collisions and body checks often result in falls to the ice, into boards, and into the goalposts.

The presence of spectators presents another potentially serious hazard to a player. The practice of throwing debris onto the ice can result in an injury. An injury usually occurs when a player's skate comes in contact with an object such as a piece of paper causing him to fall to the ice in an uncontrolled manner.

The Problem

In recent years, minor hockey organizations throughout Canada have initiated a policy, whereby, participants are required to wear protective headgear. Consequently there has been a large influx of numerous types of commercial hockey helmets. The helmets that presently appear vary in respect to their basic construction and design. The moulds of helmets are generally constructed from plastic material of various thicknesses. Some helmets are easily deformed while others are non-deformable. The outer and inner surfaces of the moulds are generally lined with plastic foam, rubber and/or leather of various thicknesses. Some helmets attempt to utilize suspension systems similar to those found in football and motorcycle helmets. The weights of hockey helmets range from eight to twenty-two ounces.

The purpose of the study is to evaluate commercial hockey helmets for their ability to absorb energy at selected sites from standardized blows.

Sub-Problem

To determine change, if any, in the ability of the helmets to absorb energy when the velocity of the blow is varied.

Definition of Terms

Kinetic Energy equals one-half the mass times the velocity squared.

If the combined mass of the headform and helmet is considered to be

constant for all helmets, then the velocity squared is proportional to kinetic energy. Therefore, for comparative purposes in the study, kinetic energy is proportional to the area squared under the acceleration-time curve.

Acceleration is the time rate of change of velocity of a body and is usually expressed in 'g' units, where 'g' equals 32.2 feet per second per second or 386 inches per second per second.

Peak Acceleration is the maximum rate of change of velocity. Peak Acceleration is the maximum point in the acceleration-time curve.

Accelerometer is an electro-mechanical transducer that produces a voltage output that is directly proportional to acceleration.

Delimitations

The results obtained in the study are not intended to serve as a criterion for determining the "safest" commercial hockey helmets.

The sample is limited to ten different hockey helmets.

The parameters analyzed are limited to kinetic energy and peak acceleration.

Limitations

The blows were inflicted at right angles to the helmet.

The areas tested were the front and back positions.

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CHAPTER II

RELATED LITERATURE

The review of the literature is presented in the following topical order: Medical aspects of head injury; Impact studies conducted on dogs and human cadavers; Impact studies conducted on various types of headforms; and Impact studies conducted on human beings.

Medical Aspects of Head Injury

All injuries are the result of the absorption of energy by the head (1). Energy will be absorbed by the head whenever it comes in contact with an object that is moving at a different velocity. In impacts to the head, the energy that causes injury results from acceleration, deceleration or compression of the head and neck (1, 2, 3, 4). Acceleration and deceleration cause an increase in intra-cranial pressure and mass movements of the intra-cranial contents at the time of impact (2, 5, 6, 7).

The head may be subjected to either direct or indirect blows (1, 2). In a direct blow, a moving object (puck or stick) contacts the non-moving or slower moving head resulting in acceleration of the skull and contents. In an indirect blow, the moving head and body may come in contact with non-moving (ice) or slower moving object resulting in rapid deceleration of the skull and contents.

The energy absorbed by the skull and contents will not be the same as the energy possessed by a moving object prior to the time of impact. The scalp and hair of an individual offers excellent protection

against skull fracture due to impact (1, 6, 8, 9). It has been reported that an empty cadaver skull can fracture with an absorption of 25 inch pounds of energy. To produce a fracture in a human cadaver with the scalp and hair intact, approximately 400-600 inch pounds of energy is required. At this level, records of acceleration average 112 g with peaks of 200 g. Based on the reported findings, the investigators felt that when a linear fracture was obtained in the human cadaver, a moderate to severe concussive effect would occur (8, 10). A fracture without a concussion can occur, but most fractures are usually accompanied by a concussion.

Impact Studies Conducted on Dogs and Human Cadavers

Studies of impact involving human cadaver heads and dogs under anesthesia have been reported. The findings reported, if applied to human beings, could possibly serve as a criteria for minimal acceptable standards for protective headgear.

Using dogs of various weights and under anesthesia, Haddad, Lissner, Webster and Gurdjian (11) attempted to determine the relation of acceleration to physiological effects. The investigator employed an accelerometer which was secured to the skull on the side opposite that which was struck. Padded ball peen hammers were used to deliver blows to the head. Records of blood pressure and respiration were taken. A concussive effect was considered to be present if definite vasomotor and respiratory responses were obtained.

Of the thirty-four dogs used in the experiment, nine showed no

concussive effect. The nine dogs in this group were subjected to acceleration values ranging from 113 g to 750 g. Twelve dogs showed minimal concussive effects and the acceleration values ranged from 250 g to 650 g. Ten dogs received severe concussive effects and the magnitude of acceleration varied from 72 g to 650 g.

The authors reported that there is no constant relationship between the magnitude of acceleration and the physiological response obtained.

Gurdjian, Hodgson, Hardy, Patrick and Lissner (8), conducted two experiments designed to evaluate the protective characteristics of helmets most commonly used in sports. The first experiment was conducted using mongrel dogs under anesthesia and the second experiment used human cadaver heads. In both experiments, the effectiveness of protection of one-eighth inch fibre glass, one-quarter inch rubber, one-half inch and five-eighths inch bucolite, bucolite helmet patch and combinations of these substances, and certain manufactured helmets were studied.

In the first experiment, dogs of various weights were subjected to blows from a two pound rotary hammer driven by compressed air. The velocity of the hammer could be varied over a wide range of values. The degree of concussion was evaluated over a wide range of impact velocities with or without use of the protective material. To measure the degree of concussive effect, the corneal reflex as well as continuous recordings of blood pressure, pulse, and respiration rates were obtained. Concussive effects were termed mild, minimal, moderate, and severe. A piezoelectric type accelerometer was attached to the skull of the dog. The output from the accelerometer was fed into an oscillograph and the energy and impulse was computed from these records.

The investigators reported the data for five dogs and, since the findings were quite similar, the results of one dog are reported here. The dog was struck with the two pound hammer at a velocity of 25 feet per second. When protective material of one-eighth inch fibre glass over five-eighths inch bucolite padding was used to protect the head, the dog sustained a minimal concussion. An identical blow with the protective patches removed resulted in a minimal to moderate concussion. With only a one-eighth inch fibre glass plate in position and the velocity increased to 31 feet per second, the animal sustained a moderate concussive effect. The same blow with the protective plate removed resulted in a severe concussive effect. It should be noted at this point that the investigators used the same dog for several impacts.

Based on the results obtained from the dogs, the investigators reported the appearance of a linear relationship between kinetic energy and the degree of concussive effect. It was found that an obvious difference in the effect occurred when the head was fixed or free to move.

In the human cadaver experiment, specimens were mounted onto a sled on vertical tracks. The height of the sled could be varied thus producing different velocities and impact energy. The heads were positioned over the end of the sled so that the forehead area struck a steel block. At a point diametrically opposite to the point of impact, piezoelectric accelerometers were mounted. The method employed was to measure the accelerations with no helmet followed by a similar type of drop with the helmet in place. This aspect of the study was based on the principle of a protection index. The protection index, as utilized by the authors, is a ratio of impact velocity with the helmet on, to

the impact velocity without a helmet.

In comparing the two methods, the drop test and the rotary hammer test, the investigators reported that the energy absorbed by the helmet and contents is maximum in the drop test because the impacted surface does not move. The investigators failed to report any differences found among the protective materials as well as the protective helmets used in the experiment. However, it was reported that a helmet with a suspension system is inferior to one padded with energy absorbing material. A helmet with a hard shell which will not be deformed due to impact, offers considerable protection from skull fracture. Another finding, that often is overlooked and misinterpreted, is that prevention of skull fracture is not a guarantee against a concussion or brain damage.

In a follow-up study on results obtained in a previous study utilizing human cadavers (8), Gurdjian, Roberts, and Thomas (10) reported further findings. They reported that "in the case of the human cadaver, the energy required to produce a linear fracture is important and may be used as an assumptive level of energy for a moderate concussive effect". With this assumption, it was reported that there was an average acceleration of 112 g, with peak accelerations up to 200 g's, and an increase in the intra-cranial pressure of about 30 pounds per square inch. As an outcome of these findings, the investigators computed a tolerance curve for the human head. Upon examining the curve, it becomes evident that approximately 50 g can be tolerated by a human head for many milliseconds. Acceleration values above 150 g can be tolerated for only a fraction of a millisecond. The investigators point out that care must be taken in using a curve of this nature in that the direction

in which a blow is applied can be very critical. The curve was computed from linear impacts to the frontal area at an angle of 30 degrees.

Further information is reported regarding the protection index employed in the previous study. Upon examining the graph constructed by the investigators, it becomes evident that different helmets at the same impact velocity produce different accelerations. The investigators conclude that it is hoped that with the help of the tolerance curves, effective protective devices may be constructed.

Impact Studies Conducted on Various Types of Headforms

Snively, Kovacic and Chichester (12) conducted an experiment designed to evaluate football helmets. The investigators subjected a number of commercial football helmets and several experimental helmets to selected impact measurements. The helmets were placed on a metal headform in which was fitted a piezoelectric accelerometer. A known amount of energy was impacted by dropping upon it a striking bob. The weight and height of the drop could easily be varied thus changing the amount of energy impacted. The head support pivots upon impact thus providing for an essentially free moving mass. The accelerations that the accelerometer was subjected to were amplified, imposed on the screen of a cathode-ray oscilloscope, photographed and analyzed. The resultant tracings took the form of acceleration-time curves.

The investigators found that a helmet displayed excellent energy attenuation when a low order of acceleration developed and the resultant energy was dissipated over a broad base in terms of time. A

helmet displaying poor energy attenuation was one where rapid development of acceleration occurred. In general, it was found that most of the protection offered by football helmets is in the area of the crown. In suspension type helmets, poor protection was offered in the lower rear area. The common fault found with suspension helmets was that when blows produced a relaxation of the webbing, solid contact occurred, resulting in complete transmission of energy to the metal test head. The investigators reported that the helmet displaying the superior energy absorbing ability in the laboratory, was the prototype. The prototype helmet, which utilizes energy absorption design principles similar to racing helmets, was designed by the investigators.

Alexander (13) conducted an experiment designed to evaluate thirteen brands of football helmets on the basis of certain impact measurements. The helmets were fitted onto a wooden headform suspended from the ceiling by two steel cables. A metal pendulum weighing 4.58 pounds was used to strike the helmet and headform. The height of the pendulum could be varied to produce different velocities. An accelerometer in the wooden head and an accelerometer at the back of the pendulum were employed to detect impact effects. The disturbance given off by the two accelerometers were fed into a dual beam oscilloscope, photographed, projected and analyzed. From the data, maximum acceleration, maximum deceleration, and rate of acceleration were calculated. The helmets were ranked according to the impact measurements obtained at each velocity.

The author reported that the helmets varied in their ability to absorb energy according to the positions tested and the velocities

employed. In comparing the back position with other positions on the helmet, the back of eleven helmets responded poorly. In general, leather and rubber shelled helmets were inferior to the plastic-type helmet. Helmets with pliable plastic type shells and padded suspension liners were superior to hard brittle shells with canvas suspension systems.

Using the same method and apparatus as Alexander (13), Nelson (14) attempted to evaluate and compare measurements employed by Alexander in evaluating football helmets. Four measurements for both acceleration and deceleration were compared: (1) peak or maximum acceleration; (2) rate of change of acceleration; (3) time duration of acceleration; and (4) kinetic energy.

After analyzing the data obtained on thirteen brands of football helmets, it was found that the measurement of peak acceleration alone is sufficient under the given testing conditions. The author reported that observing the phenomena of deceleration of the striker is unnecessary for this type of helmet testing.

In a later study conducted by Nelson, Alexander, Montoye, and Van Huss (15), similar findings were reported. The same methods and test apparatus employed in earlier studies by Alexander and Nelson (13, 14) were utilized.

The authors reported a positive relationship between peak acceleration and rate of acceleration. An apparent relationship between acceleration and deceleration values for time duration was obtained. When kinetic energy of the helmet and headform was compared to kinetic energy lost by the pendulum, very low dependence occurred.

The findings reported by the authors are predictable in that to obtain a sharp rise in acceleration, a short duration of time is required for the rise to occur. Since energy cannot be created nor destroyed, a portion of the kinetic energy of the pendulum is converted into other forms of energy. In an impact between two colliding bodies, kinetic energy possessed by the bodies is converted into heat, sound and mechanical energy (to deform the helmet and pendulum). Thus a low dependence between kinetic energy of the headform and kinetic energy lost by the pendulum is to be expected.

Kovacic (16) conducted a study to determine the energy attenuation qualities of commercial and experimental football helmets. A secondary phase of the study was concerned with determining areas of weakness and to determine which was the best helmet design. The method and procedure was identical to a previous study conducted by Snively, Kovacic and Chichester (12).

Based on previous findings by researchers in the field, Kovacic, for the purpose of his study, stipulated that 112 foot pounds impact energy is the minimal level for adequate head protection. Helmets were coded and ranked in terms of overall resistance to "bottoming". Based on his findings, the author concluded:

"A helmet containing slow-rebound material and a soft plastic shell to attenuate high energy impact is less effective than a helmet that has a hard shell, an inner liner of foamed, non-resilient plastic next to the shell, and a soft, slow-rebound plastic form next to the head" (16:426).

In the source consulted, the author failed to supply any data whatsoever as to dominant areas of weakness in football helmets.

Using crash helmets of race car drivers who survived serious

crashes, Snively and Chichester (17), attempted to determine the forces the helmets had experienced. The study was based on the principle that racing crash helmets utilize an energy absorbing system of a non-resilient, foamed plastic which crushes upon impact. The investigators attempted to duplicate the impact impressions of ten helmets onto non-deformed, but similar types of helmets under laboratory conditions.

The apparatus and test set-up was identical to a previously reported study (12) on football helmets conducted by the same authors. The only difference being that a 1.9 inch bob was selected as representative of the most severe test conditions.

The investigators reported that six helmets showed linear deflections indicative of head accelerations well above 200 g. Three crash helmets attained values of 450 g or more.

Hendler and Wurzel (18), reported that a unique test device designed to evaluate protective headgear had been utilized in the United States Navy Aeronautical Material Equipment Laboratory. This test device consists of a platform upon which a wooden headform is mounted. The platform is dropped onto a pneumatic spring and rebounds after contact. The pneumatic spring is designed so that various magnitudes and shapes of acceleration-time curves can be obtained. The helmet and headform can be placed in any desirable position and can be directed to strike upon surfaces of various shapes.

Accelerometers are connected directly through cables to a high speed recording oscillograph. Recordings of the displacement of the platform and head during acceleration and deceleration can readily be obtained. Pressure transducers placed between the headform and helmet

enable researchers to obtain pressures developed at various locations over the headforms.

The authors report advantages the test device possesses over previous test devices. One advantage is that velocities up to 80 feet per second can be attained. Factors readily controlled are the application and location of force to the helmet, and the area of the helmet upon which the force is applied.

No information is reported on the evaluation of certain types of headgear. The investigators reported that since the head is particularly sensitive, comfort to the individual is a primary consideration in the design of helmets. Factors considered in this respect are proper fit, efficient ventilation, light weight, and freedom from localized pressure areas.

The authors conclude by stating criterion for force distribution.

"In general, the helmet which causes an external localized force of given characteristics to be changed to low pressures through distribution over the head surface, is preferable to one resulting in high pressure.

The protective helmet which distributes forces to parts of the head in proportion to the ability of these parts to withstand injury is preferable to one without this characteristic" (18:69).

Impact Studies Conducted on Human Beings

Lombard, Ames, Smith and Roth (19), using graduate students and research workers for subjects, attempted to determine the limits of acceleration due to blows to the head which a human would voluntarily tolerate. In order to distribute the forces and minimize the local effect of blows to the head, the subjects wore protective headgear

similar to those used by football players and aviation test pilots.

The striker was a pendulum of mass approximately equal to that of the head and headgear. The pendulum was suspended from the ceiling by four wires. In the steel head of the pendulum was mounted a strain gauge type accelerometer.

The authors reported that the maximum energy tolerated for blows to the top of the head was 8.7 foot pounds. The maximum g values was 34 with the average being 23 g's. Blows to the front of the head for all helmets were voluntarily limited to a maximum of 5.4 foot pounds. The maximum acceleration value was 38 g and the average 22 g. The maximum energy tolerated to the side was 8.7 foot pounds. The maximum acceleration value was 25 g with the average 20 g. The maximum energy of blows to the back was 6.5 foot pounds. The maximum acceleration value was 35 g and the average 18 g.

The limiting factors of blows to all four areas were generally of the type whereby the subject experienced local bruising, a general uncomfortable jolt, and neck pains. A limitation of the study was the control of psychological variables which are introduced when human subjects are employed in such a testing situation.

The authors concluded that accelerations of the human head of 38 g were tolerated by the subjects without any objective or subjective symptoms of concussion. In nearly all cases, the voluntary limitation of the energy of blows to the head reflected the subjects reluctance to tolerate local bruising and pain.

Reid, Tarkington, and Healion (20) used radio telemetry in the study of head impacts in football. The purpose of the study was to

investigate impact forces as they relate to the football helmet, locate blows on the helmet, and to obtain the frequency of various blows during actual games. After numerous pilot studies and revisions in the equipment, a miniature telemetering system was attached to a football player for the duration of one full season. The system consisted of a triaxial accelerometer and antenna in the helmet which in turn were connected by cables to the remainder of the equipment (batteries and transmitter) mounted on the shoulder pads. The system was previously tested during actual game situations and did not interfere or restrict the action or movement of the player. The procedure was to have the signals given off by the accelerometer transmitted to a location in the press box. The signals were coupled with an observer's description of the action as well as with slow-motion pictures. This gave the researchers "adequate monitored data to analyze the force of impact".

"The g values that were collected ranged from 71 g to 5,160 but eighty-five per cent of the blows registered 400 g's or less and ten per cent of the blows registered g's in the range of 400 - 600. Only five per cent of the impacts produced g's over 1000. During fifty per cent of the time, the instrumented player encountered no contact and during these plays the accelerometer in the helmet was not activated. The time during which force was acting ranged from 1 to 150 milliseconds, but most pulse durations were two milliseconds." (20:29).

The authors were aware of the fact that by using only one subject, no statistical significant data could be secured. In the future, more instrumented players were to be monitored.

Summary of the Related Literature

The most reliable instrument for measuring the varied effects of

dynamic force on man is man (5). In laboratory studies involving impact, the use of human beings is not practical. Investigators, evaluating protective helmets in laboratory environments, have developed various types of headforms to serve as substitutes for human heads. To detect impact effects, investigators have employed various types of accelerometers. A limitation encountered in studies of this nature is that the findings reported cannot be directly applied to determine the "safest" helmet for any one human being. Biological variables exist among human beings. Variables such as the thickness of the scalp and hair, age, state of health, and possibly the sex and race of individuals must be taken into consideration (4). Therefore, what may be a safe helmet for one individual may not necessarily be a safe helmet for another individual.

Many variables must be considered in determining the effects of blows to helmets and headforms. Studies evaluating protective helmets in laboratory environments must be designed to either control or make allowance for factors capable of influencing impact phenomenon. Impact tolerance is a function of the following factors (21).

- (1) impact location
- (2) direction of the impact
- (3) surface area in contact
- (4) surface hardness
- (5) surface roughness
- (6) impactor mass
- (7) impactor shape
- (8) impactor velocity

(9) time duration

Based on the review of the related literature and selected readings (22, 23, 24), an ideal helmet should possess the following characteristics.

- (1) Reduce the magnitude of the blow to the head.
- (2) Distribute the remaining force received by the head over as large an area as possible.
- (3) Prevent minor as well as severe injuries.

Helmets are, or should be, designed for a specific sport (6, 8). More specifically, hockey helmets should be designed and constructed to absorb blows of large mass-low velocity, and small mass-high velocity (25). For blows of high velocity-small mass, the hockey helmet should distribute the impact energy over a large area to the scalp and skull and much lower in magnitude (26). For blows of this nature, helmets should be constructed out of a hard and rigid shell (6, 26). For impacts of low velocity-large mass, the inside of the helmet should consist of energy absorbing material of given thickness to limit the deceleration forces (25).

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CHAPTER III

METHODS AND PROCEDURES

Experimental Apparatus

The experimental apparatus consists of four component parts: a pendulum impact arrangement; a pendulum release mechanism; a wooden headform; and recording instruments.

The pendulum impact arrangement, as shown in Figure 1, was provided by a steel bar measuring 49-1/2 by 2 by 1 inches and weighing 27.7 pounds. The bar was securely fastened to a bearing support of one inch diameter which rotated on two pillar blocks fastened to the top of a reinforced Dexion framework. The framework was attached to two wooden skids which in turn were fixed to a concrete floor. In this way, no displacement of the pendulum and framework could occur during and after impacts.

The point of impact corresponded to the centre of percussion of the bar located 32 inches from the bearing support. At the centre of percussion, a flat section of a hockey stick shaft was attached to provide for uniformity of blows to the helmets (Figure 2). The maximum area of contact at the time of impact was 1.75 square inches. A known amount of energy was applied via the pendulum arrangement and the vertical height from which the pendulum was released could be varied thus changing the impact velocity.

An electro-magnetic release mechanism, as shown in Figure 3, ensured a constant release for the pendulum. A one-sixteenth inch steel cable attached to the end of the pendulum and a latch, respectively,

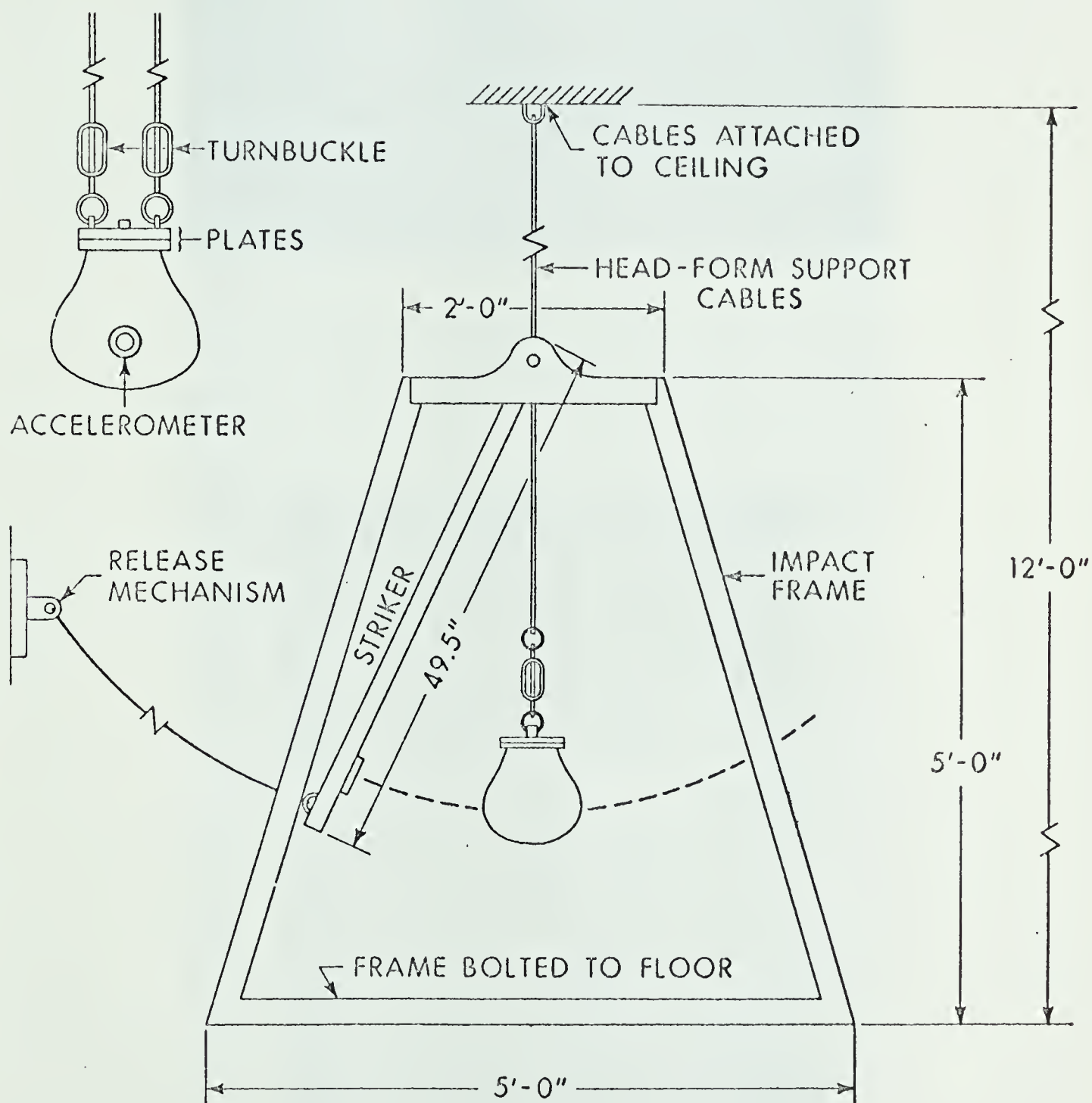


FIGURE 1

SIDE VIEW OF PENDULUM IMPACT ARRANGEMENT

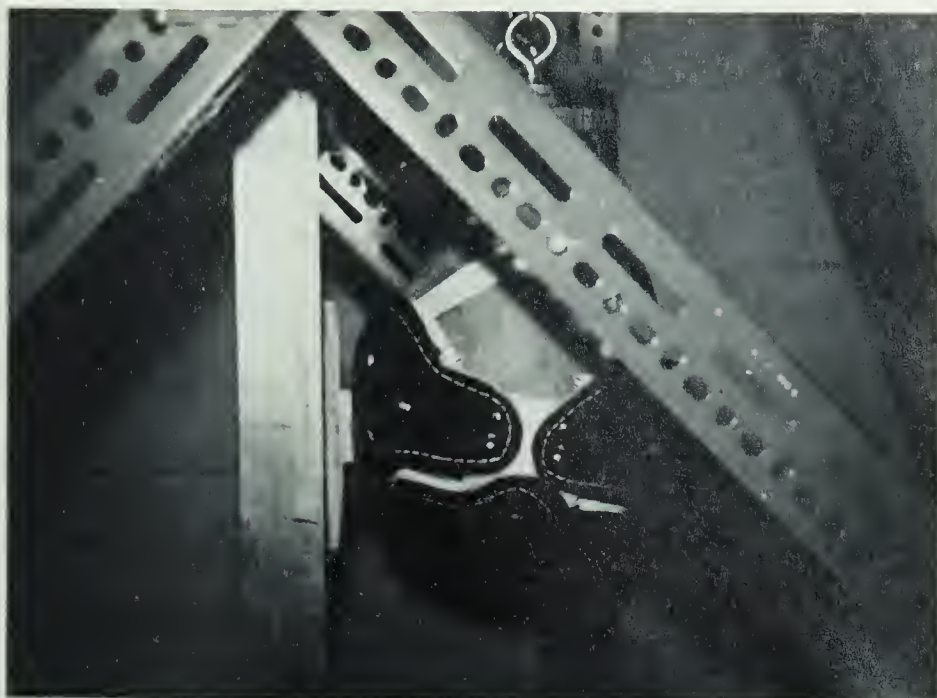


FIGURE 2

FLAT SECTION OF A HOCKEY
STICK SHAFT



FIGURE 3

ELECTRO-MAGNETIC RELEASE MECHANISM

was employed to set the pendulum for release. When the switch was pushed, the electro-magnet pulled the latch down causing the cable and pendulum to release. Three different lengths of the cable, corresponding to three different vertical heights of the striking surface, were utilized to vary the impact velocity. The three vertical heights, two inches, four inches and six inches, produced impact velocities of 39.3 inches per second, 55.6 inches per second, and 68.1 inches per second, respectively.

The pendulum struck a laminated oak headform suspended from the ceiling by two steel cables and a turnbuckle arrangement. The top of the two cables were attached to adjustable clamps which in turn were fastened to beams in the ceiling. Two turnbuckles attached to the bottom of the two cables enabled the headform to be raised and lowered to ensure that the striking surface of the pendulum struck a constant position on the helmet. Paint was applied to the threads of the turnbuckles to ensure that the headform did not slip after a blow was delivered. The two turnbuckles were attached to two eye hooks welded on the upper surface of a round steel plate. The plate was in turn attached to permanent steel plate located at the bottom of the inverted headform. The top plate was adjustable so that the centre of the headform could be lined up with the centre of the striking surface. The plates, headform, and pendulum are shown in Figure 4.

A bolt, as shown in Figure 5, was inserted and fastened inside the headform. The ends of the bolt corresponded to the front and back positions of the headform. The ends were tapped to provide a stable mounting surface for the accelerometer. The combined weight of the

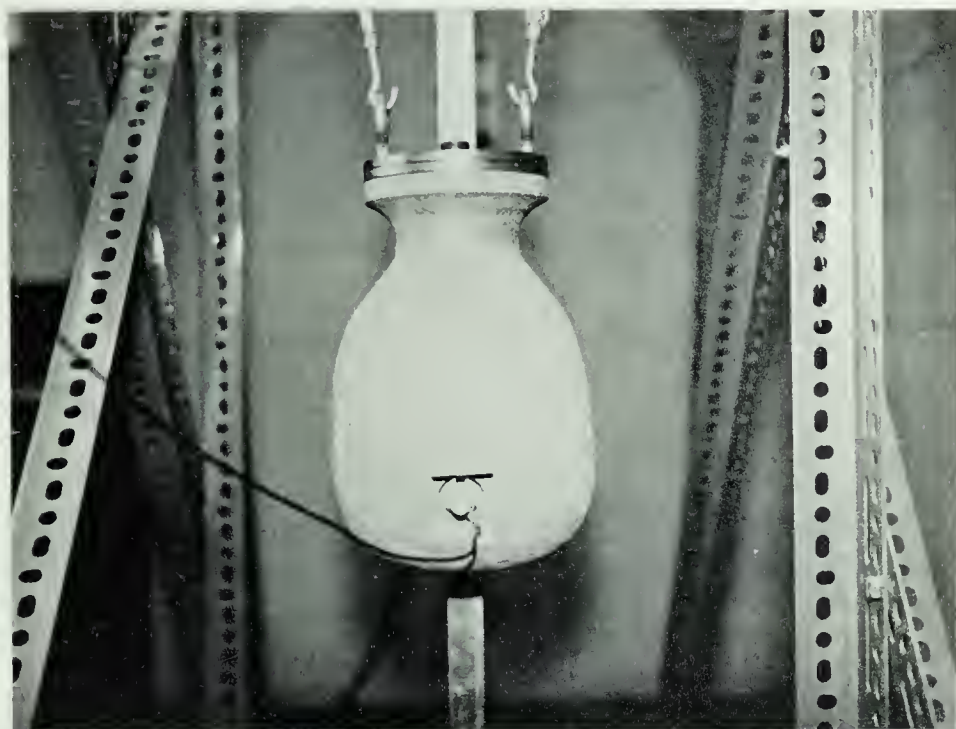


FIGURE 4
CENTERED PENDULUM AND HEADFORM

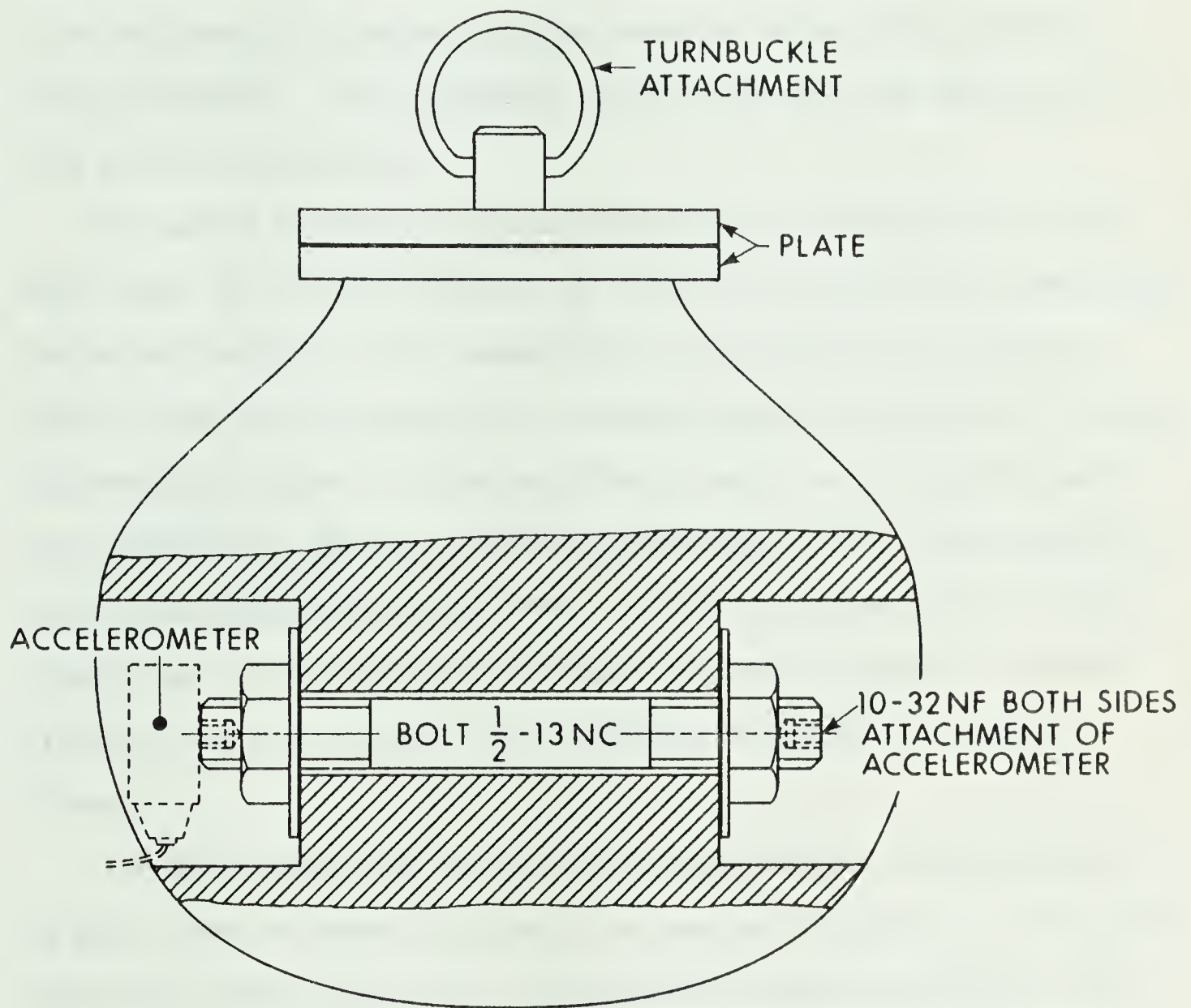


FIGURE 5

SIDE VIEW OF HEADFORM WITH INSERTED
BOLT FOR ACCELEROMETER ATTACHMENT

headform, bolt, two plates and one-third the cable weight was 9.2 pounds.

A Bruel and Kjaer 4332 piezoelectric accelerometer was mounted diametrically opposite the point of impact. The accelerometer and bolt were connected by an insulated stud. The mounting employed resulted in an acceleration directed from the mounting surface into the body of the accelerometer. This alignment corresponded with the accelerometer's main axis of sensitivity.

The output terminal of the accelerometer was connected by a one metre cable to the input terminal of a Bruel and Kjaer 2616 preamplifier. The output terminal of the preamplifier was connected by a one metre cable to the input terminal of a Tektronix Type 564 Storage Oscilloscope, complete with a Type 3B3 Time Base Plug-In Unit, and a Type 3A1 Dual-Trace Amplifier. The two one metre cables were factory calibrated for the accelerometer and preamplifier. In this arrangement, the voltage output from the accelerometer was amplified and displayed as a visual signal on the oscilloscope. The recording arrangement is shown in Figure 6.

The oscilloscope was set at single sweep and the range was set, so that, when the impact occurred, the beam was triggered and travelled across the screen only once. This procedure recorded only the initial impact. The visual signals, which were acceleration-time curves, were stored on the graticule of the oscilloscope. The stored curves were then photographed with a Polaroid Land Camera, as shown in Figure 7, for permanent records.

The ten hockey helmets tested are described in detail in Appendix A.

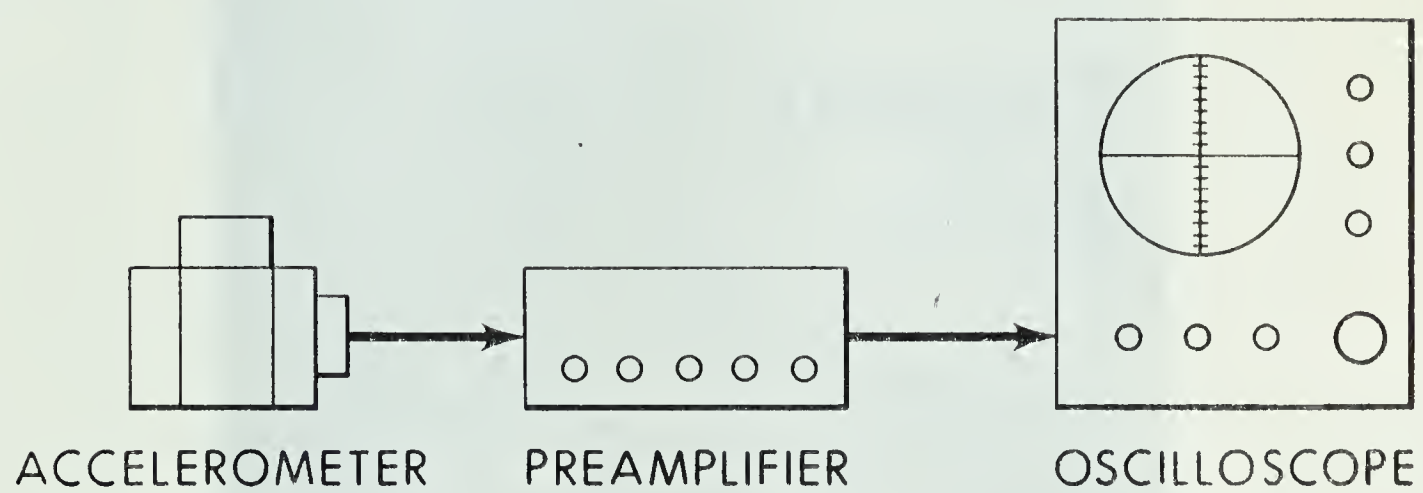


FIGURE 6

RECORDING INSTRUMENTS

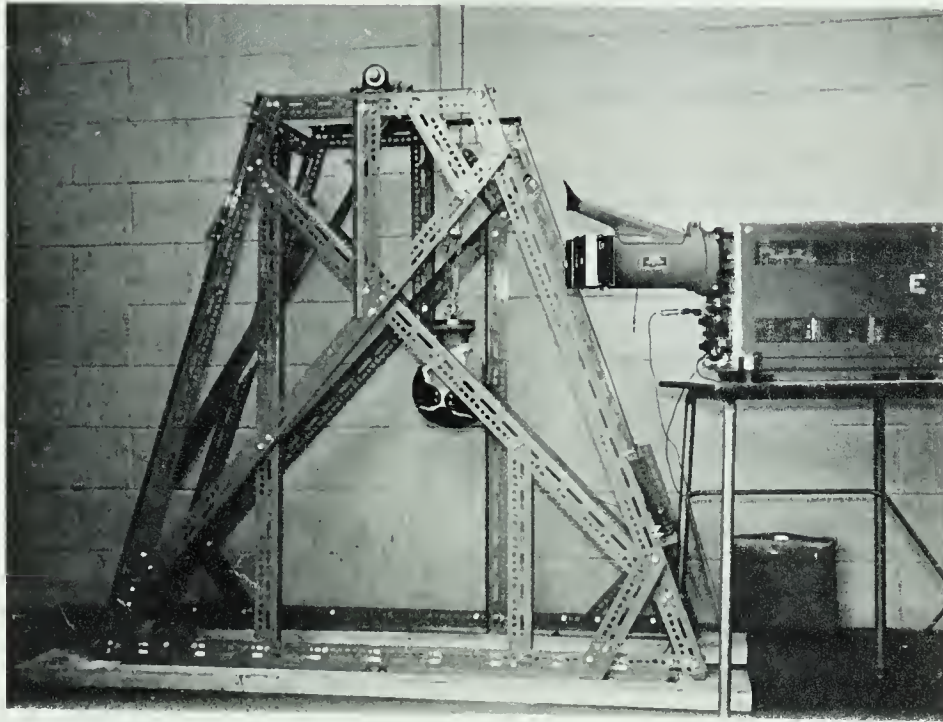


FIGURE 7

TEST SET-UP SHOWING OSCILLOSCOPE
WITH CAMERA ATTACHMENT

Testing Procedure

For operational efficiency, two technicians were employed. The operation of the oscilloscope, camera and manipulation of the helmets were controlled by the first technician. The second technician was responsible for the control of the release switch and the resetting of the pendulum after each impact.

The headform was designed to accommodate a size seven and one-quarter helmet. The helmets were adjustable so that a proper fit could be secured. A standard procedure was employed to fit the helmets onto the headform. Markings on the front and back of the headform ensured that the helmets covered the same portion of the headform.

Prior to a blow being delivered, the headform and helmet and pendulum were lined up. The head and helmet remained stationary prior to the impact. Adjustable clamps attached to the ceiling moved the head in a horizontal plane. The distance and direction moved depended on the helmet design and the thickness of the material used to construct the helmet. This procedure ensured that the pendulum struck the front and back positions of the stationary, suspended headform, at ninety degrees for each impact trial. At ninety degrees to the helmet the pendulum possessed maximum kinetic energy.

The helmets tested had not been subjected to previous blows. The front position was tested first. The order of the three vertical heights of the pendulum were two inches, four inches and six inches. Helmets tested at any one velocity were selected randomly. Three readings for each helmet, at each velocity, were recorded. The same procedure was repeated for the back position.

CHAPTER IV

ANALYSIS AND RESULTS

Peak Acceleration

Peak acceleration was determined by measuring the height of the peak from the baseline of the acceleration-time curve in each photograph. A scale effect between the graticule of the oscilloscope and polaroid film was found to exist. To obtain true values, the peak value was multiplied by a correction factor of 1.075. The peak value, measured in centimeters, was multiplied by the voltage or vertical sensitivity of the oscilloscope and converted into millivolts. By dividing millivolts by the sensitivity of the accelerometer (48.8 mV/g), peak acceleration was expressed in g units.

The acceleration-time curves took the form of terminal saw-tooth, half-sine, or curves that were neither of the two. The various waveforms are found in Appendix B. In some instances the curves displayed an overshoot ranging from one to sixty per cent of the peak value. The overshoot can be attributed to the insufficient low-frequency response of the accelerometer (1). The accelerometer cannot produce a DC voltage signal and, therefore, is unable to produce a constant voltage signal. Due to this characteristic of the accelerometer, the peak value cannot be maintained.

The reduction in peak value is equal to the overshoot or one-half the overshoot depending upon whether the waveform is saw-tooth or half-sine, respectively (1). When the acceleration-time curves were either of the two, a correction factor could be applied. In some instances

the wave-forms were not any of the known shapes and no correction factor could be applied. However, in most instances the correction would be small and generally less than five per cent.

In the majority of curves analyzed, the overshoot was less than five per cent and no correction factor was applied. In cases where overshoots were much larger than five per cent, the helmets were placed in a category having high peak accelerations. Large overshoots were primarily evident at the highest striker velocity.

The helmets were ranked at each velocity, from lowest to highest peak values. Helmets displaying large overshoots were classed as inferior helmets under the given experimental conditions. In the data, these helmets are denoted by an asterisk. Tables I and II report the peak acceleration values obtained for ten helmets at the front and back positions, respectively. The peak g value is the mean of three recordings for each helmet at each velocity.

To facilitate comparisons between helmets the peak g values for helmets at the front position were plotted on a graph (Figure 8). Upon examining the graph, it appears that linear and non-linear relationships exist between the peak force absorbed by the headform and the impact velocity of the pendulum. The slopes for helmets CCM and WIN tend to increase as the velocity of the blow is increased. The slopes for helmets RID and CWM tend to decrease as the velocity of the blow is increased.

At the lowest velocity of the pendulum, the peak g values tend to occupy a small range. G's at this velocity range from twelve for the RID helmet to twenty-six for the SPL helmet. At the medium velocity,

TABLE I
RANKINGS OF HELMETS ON THE BASIS OF PEAK ACCELERATION IN G UNITS
FOR THREE RELEASE HEIGHTS OF THE PENDULUM AT THE FRONT POSITION

Helmet	2 Inches	Helmet	4 Inches	Helmet	6 Inches
RID	12	CWH	19	RID	24
CCM	12	RID	21	CWH	32
CWH	15	CCM	25	CWM	34
WIN	18	WIN	26	CCM	48
CWM	20	CWM	29	WIN	56
PER	20	CWL	32	SPH	57
SPH	22	SPM	41	CWL	57*
SPM	22	SPH	41	SPM	57*
CWL	23	PER	42	PER	57*
SPL	26	SPL	57	SPL	57*

* Large Overshoot - Much Higher Peak Acceleration than Reported

TABLE II

RANKINGS OF HELMETS ON THE BASIS OF PEAK ACCELERATION IN G UNITS
FOR THREE RELEASE HEIGHTS OF THE PENDULUM AT THE BACK POSITION

Helmet	2 Inches	Helmet	4 Inches	Helmet	6 Inches
CCM	17	SPL	27	SPH	36
CWH	19	CCM	29	SPM	40
WIN	20	SPM	30	SPL	40
SPH	20	SPH	30	RID	42
SPM	21	CWH	31	WIN	43
SPL	21	WIN	31	CCM	47
CWM	24	RID	35	CWH	52
RID	24	CWM	45	CWM	57*
CWL	26	CWL	55	CWL	57*
PER	54	PER	57*	PER	57*

* Large Overshoot - Much Higher Peak Acceleration than Reported

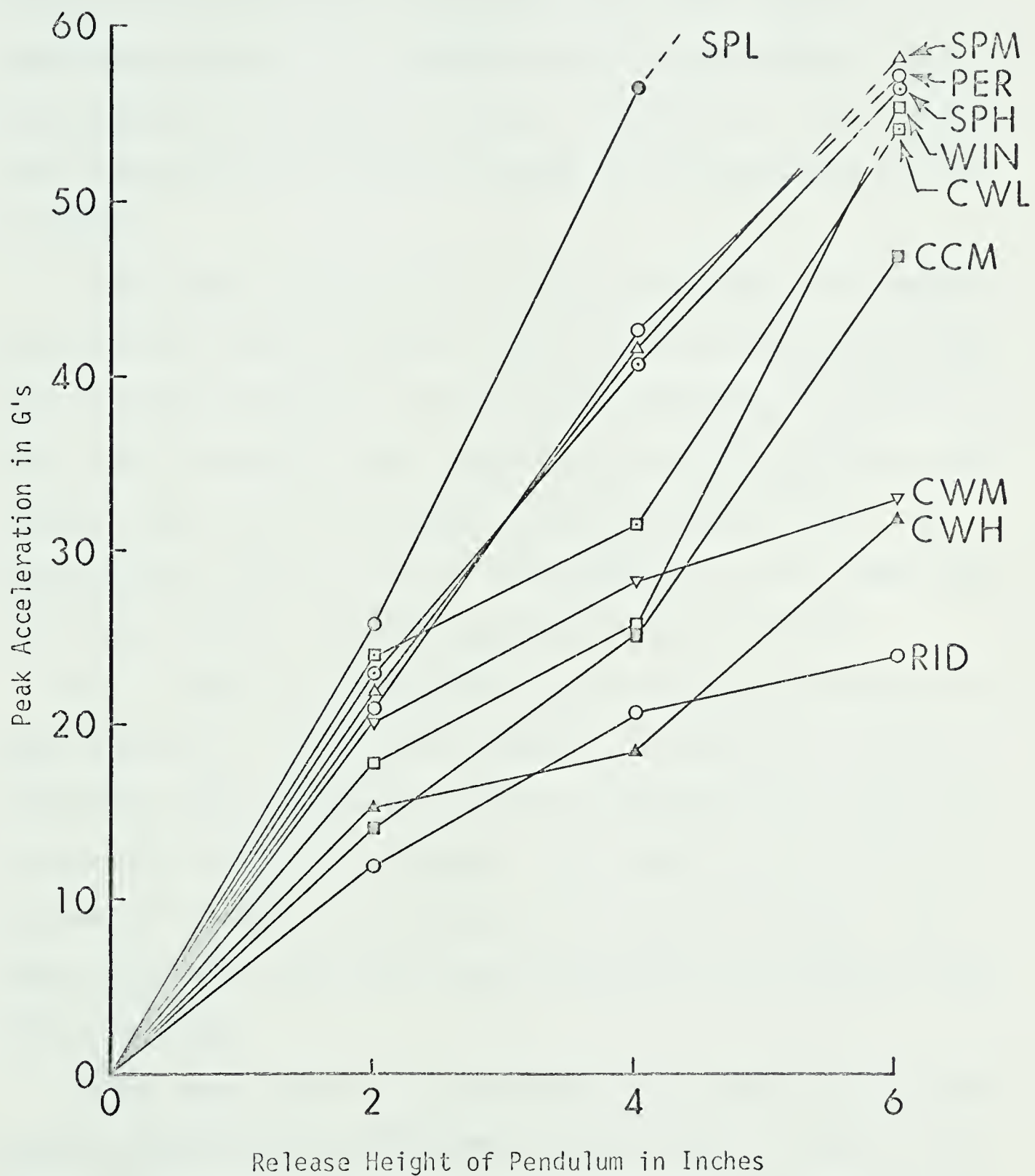


FIGURE 8

THE EFFECT OF THREE RELEASE HEIGHTS OF THE
PENDULUM ON PEAK ACCELERATION FOR TEN HELMETS
AT THE FRONT POSITION

the peak values tend to spread out. Values at this velocity range from nineteen g's for the CWH helmet to fifty-seven g's for the SPL helmet. Although not clearly shown by the graph due to large overshoots, the spread among helmets at the highest velocity of the pendulum is more pronounced than at the medium velocity. The g values at this velocity range from twenty-four for the RID helmet to fifty-seven plus for the SPL helmet.

If the highest velocity of the pendulum represents the severest test condition, then the superior helmet at the front position is the RID. The helmet attained a g value of only twenty-four g's and the slope tends to decrease as the velocity of the blow is increased. The inferior helmet at the front position would be the SPL helmet. The helmet attained a peak g value of fifty-seven plus and the slope tends to increase rapidly as the velocity of the blow is increased.

Peak g values for helmets at the back position were plotted on a graph (Figure 9). As in the front position, linear and non-linear relationships appear between the peak force absorbed by the headform and the impact velocity of the pendulum. The slopes for helmets CWH and CCM tend to increase as the velocity of the blow is increased. The slopes for helmets SPH and RID tend to decrease as the velocity of the blow is increased.

At the lowest velocity of the pendulum, the range of peak values, with the exception of the PER helmet, is quite small. Values at this velocity range from seventeen g's for the CCM helmet to twenty-six g's for the CWL helmet. The PER helmet attained a peak value of fifty-four g's. At the medium velocity, the spread is more pronounced. Peak

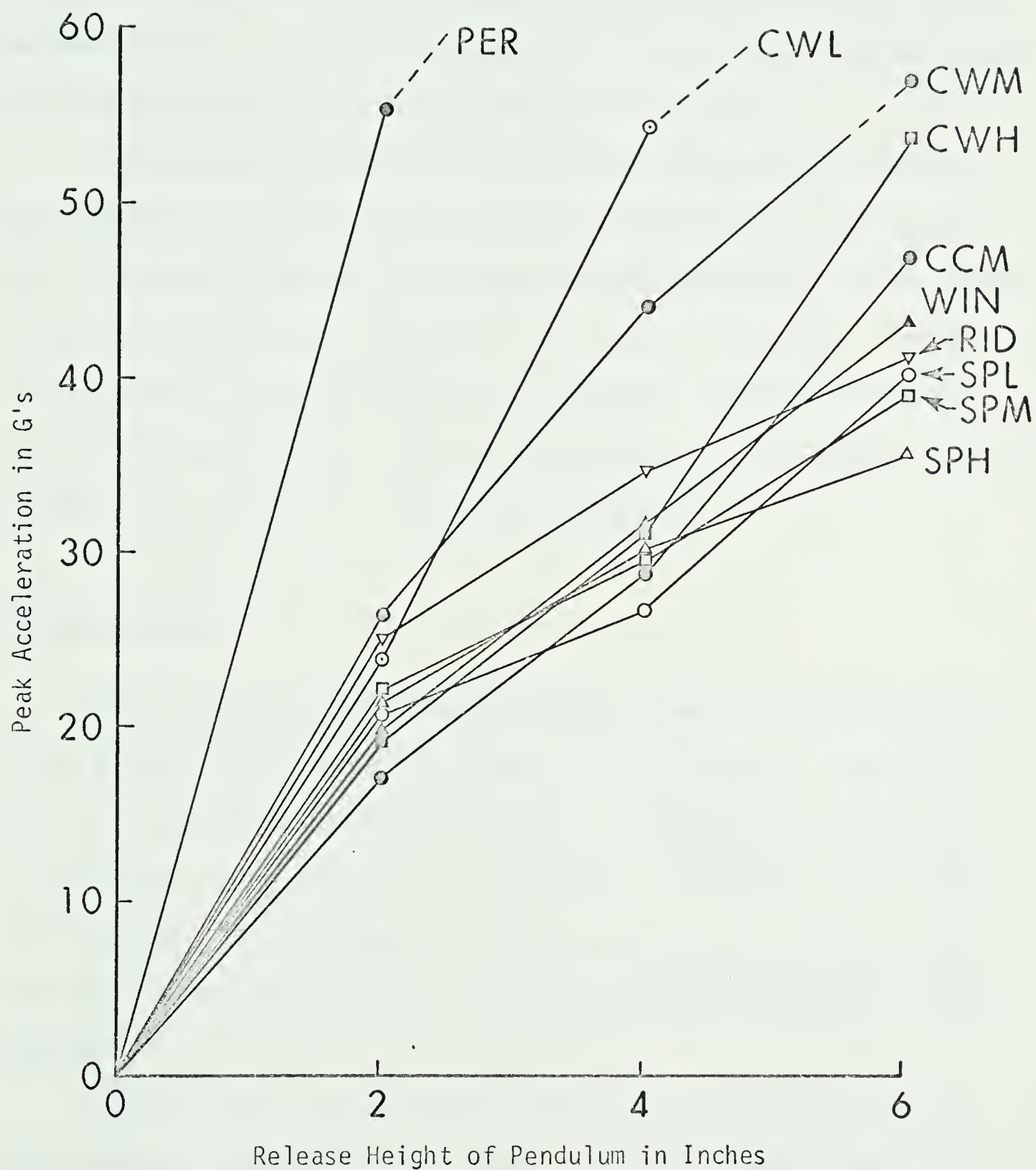


FIGURE 9

THE EFFECT OF THREE RELEASE HEIGHTS OF THE
PENDULUM ON PEAK ACCELERATION FOR TEN HELMETS
AT THE BACK POSITION

g values range from twenty-seven to fifty-seven plus for the PER helmet. Although not clearly shown by the graph due to large overshoots, the spread of peak values for the highest velocity is greater than at the medium velocity. The g values range from thirty-six for the SPH helmet to fifty-seven plus for the PER, CWL, and CWM helmets.

If the highest velocity of the pendulum represents the severest test condition, then the superior helmet at the back position is the SPH. The helmet attained a peak value of thirty-six g's and its slope tends to decrease as the velocity of the blow is increased. The inferior helmet at the back position is the PER. The helmet attained a value of fifty-seven plus at the medium velocity and its slope increases rapidly as the velocity of the blow is increased.

Kinetic Energy

Kinetic energy equals one-half the mass times the velocity squared. Since the maximum difference in weights of the helmets is only six per cent of the headform and effective mass, the headform and helmet mass is considered to be constant for all helmets. Therefore, for comparative purposes, kinetic energy is proportional to the velocity squared. The area squared under the acceleration-time curve represents velocity squared.

The area under the acceleration-time curve was calculated by a Coradi-Senior compensating planimeter. The unit of measurement was in square inches. Since the unit of measurement on the graticule of the oscilloscope was in centimeters, it was deemed desirable to convert the

planimeter readings into square centimeters. Three tracings for each recording were taken and the mean for three recordings was used. A scale effect between the graticule of the oscilloscope and the polaroid film was found to exist. To obtain true values, the area under the curve was multiplied by a correction factor of 1.16. By multiplying the corrected area under the curve by the horizontal and vertical sensitivity and dividing by the sensitivity of the accelerometer, the velocity was determined. The velocity was squared and expressed in inches per second.

Corrections for overshoots could again be applied but, in the majority of curves, the area would be increased by less than one per cent. According to Snively and collaborators (2), a helmet displays excellent energy absorbing ability when a low order of acceleration is developed and the resultant energy is dissipated over a broad base in terms of time. A helmet displays poor energy absorbing ability when high acceleration develops over a short period of time. Helmets displaying large overshoots fall into the latter category and, therefore, can be classed as inferior helmets. In the data, these helmets are denoted by an asterisk.

Helmets were ranked at each velocity of the pendulum from lowest to highest kinetic energy ($K.E. \propto V^2$) absorbed by the headform. If two helmets produced similar values, the time or base of the curves was taken into consideration. Tables III and IV report the rankings for ten helmets at the front and back positions, respectively.

To facilitate comparisons between helmets, the velocity squared values for helmets at the front position were plotted on a graph

TABLE III

RANKINGS OF HELMETS ON THE BASIS OF VELOCITY SQUARED* IN INCHES PER SECOND
FOR THREE RELEASE HEIGHTS OF THE PENDULUM AT THE FRONT POSITION

Helmet	2 Inches	Helmet	4 Inches	Helmet	6 Inches
RID	3,000	RID	5,500	RID	8,500
CWH	3,500	CWH	5,500	SPH	9,300
CCM	3,600	WIN	6,400	CWH	9,500
SPH	3,700	CWM	6,600	WIN	10,500
SPL	3,700	PER	6,800	CCM	10,700
SPM	3,700	CCM	7,000	CWM	12,200
WIN	3,700	SPH	7,100	CWL	6,300**
PER	4,000	SPM	7,800	SPM	4,700**
CWM	4,000	CWL	8,000	PER	3,500**
CWL	4,500	SPL	4,200**	SPL	3,100**

* If the Mass is Constant for all Helmets the Kinetic Energy is Proportional to Velocity Squared.
 ** Large Overshoots - Inferior Helmets Due to High Peak Accelerations Developed Over a Short Period of Time.

TABLE IV

RANKINGS OF HELMETS ON THE BASIS OF VELOCITY SQUARED* IN INCHES PER SECOND
FOR THREE RELEASE HEIGHTS OF THE PENDULUM AT THE BACK POSITION

Helmet	2 Inches	Helmet	4 Inches	Helmet	6 Inches
CWH	3,200	SPL	5,500	RID	9,100
SPH	3,200	CWH	6,200	SPH	9,300
RID	3,400	RID	6,500	CWH	9,900
SPL	3,500	SPH	6,700	SPL	10,000
PER	3,700	CWM	6,800	WIN	10,700
SPM	3,700	SPM	6,900	SPM	11,300
WIN	3,800	WIN	7,200	CCM	11,500
CWM	4,300	CWL	8,000	CWM	3,900**
CCM	4,300	CCM	8,500	CWL	3,900**
CWL	4,600	PER	2,600**	PER	1,800**

* If the Mass is Constant for all Helmets then Kinetic Energy is Proportional to Velocity Squared.

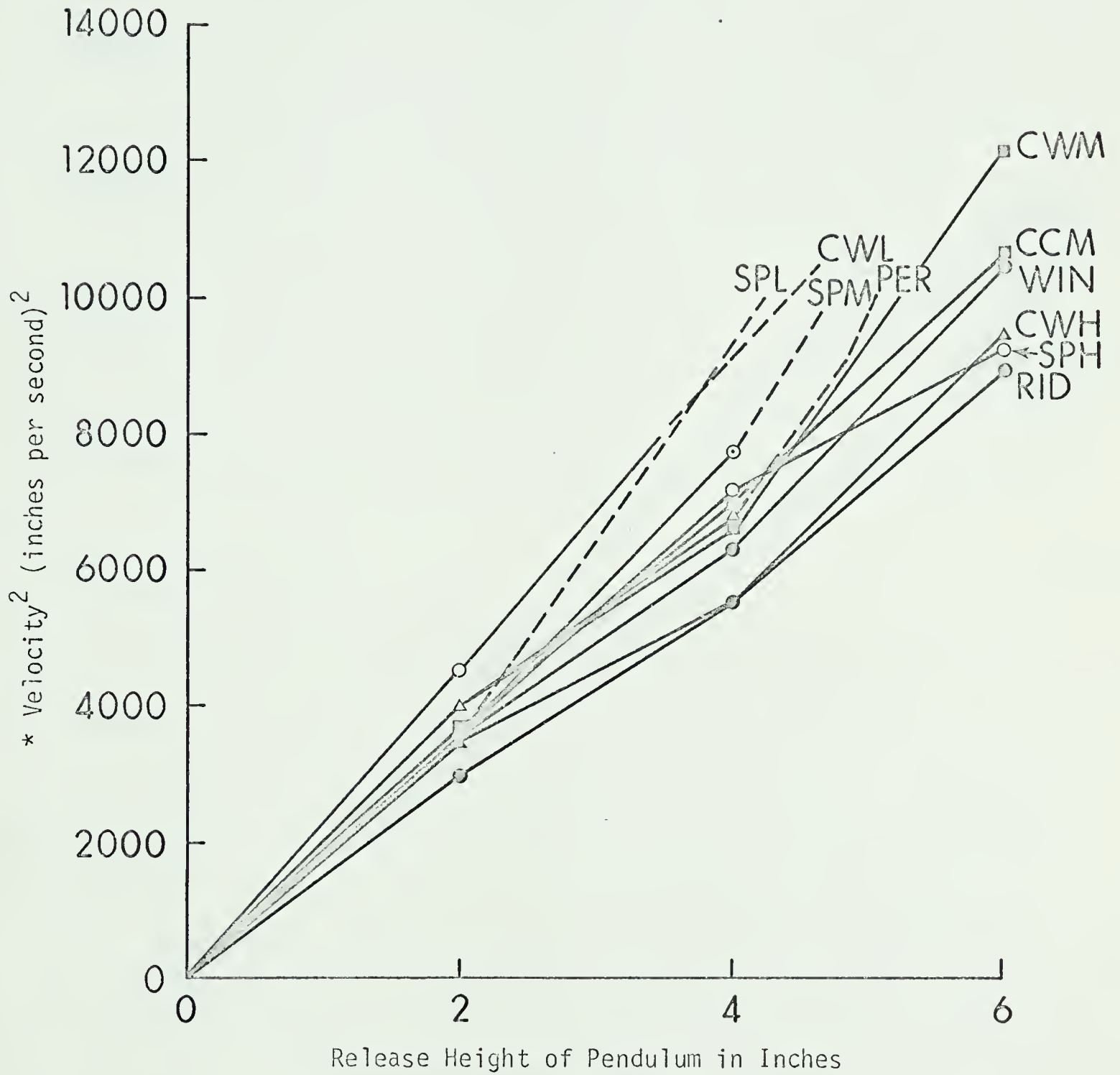
** Large Overshoots - Inferior Helmets Due to High Peak Accelerations Over a Short Period of Time.

(Figure 10). Although the values are greater if kinetic energy is plotted, the relation between helmets remains unchanged if the mass is constant. Upon examining the graph, it appears that linear and non-linear relationships exist between kinetic energy ($K.E. \propto V^2$) absorbed by the headform and the impact velocity of the pendulum. The slope for helmet SPL tends to increase as the velocity of the blow is increased. The slope for helmet SPH tends to decrease as the velocity of the blow is increased. The spread between the energy absorbing ability of helmets tends to increase as the velocity of the blow is increased.

If the highest velocity of the pendulum represents the severest test condition, then the superior energy absorbing helmets at the front position are the RID, SPH, and CWH. Inferior helmets at the front position, due to large overshoots and high peak accelerations developed over a short period of time, are the SPL, CWL, SPM, and PER.

Upon examining the graph for the back position (Figure 11), it appears that linear and non-linear relationships exist between the kinetic energy ($K.E. \propto V^2$) absorbed by the headform and the impact velocity of the pendulum. The slopes for helmets RID and SPH tend to decrease slightly as the velocity of the blow is increased. The slopes for helmets PER and CWL tend to increase as the velocity of the blow is increased. The spread between the energy absorbing ability of helmets tends to increase as the velocity of the blow is increased.

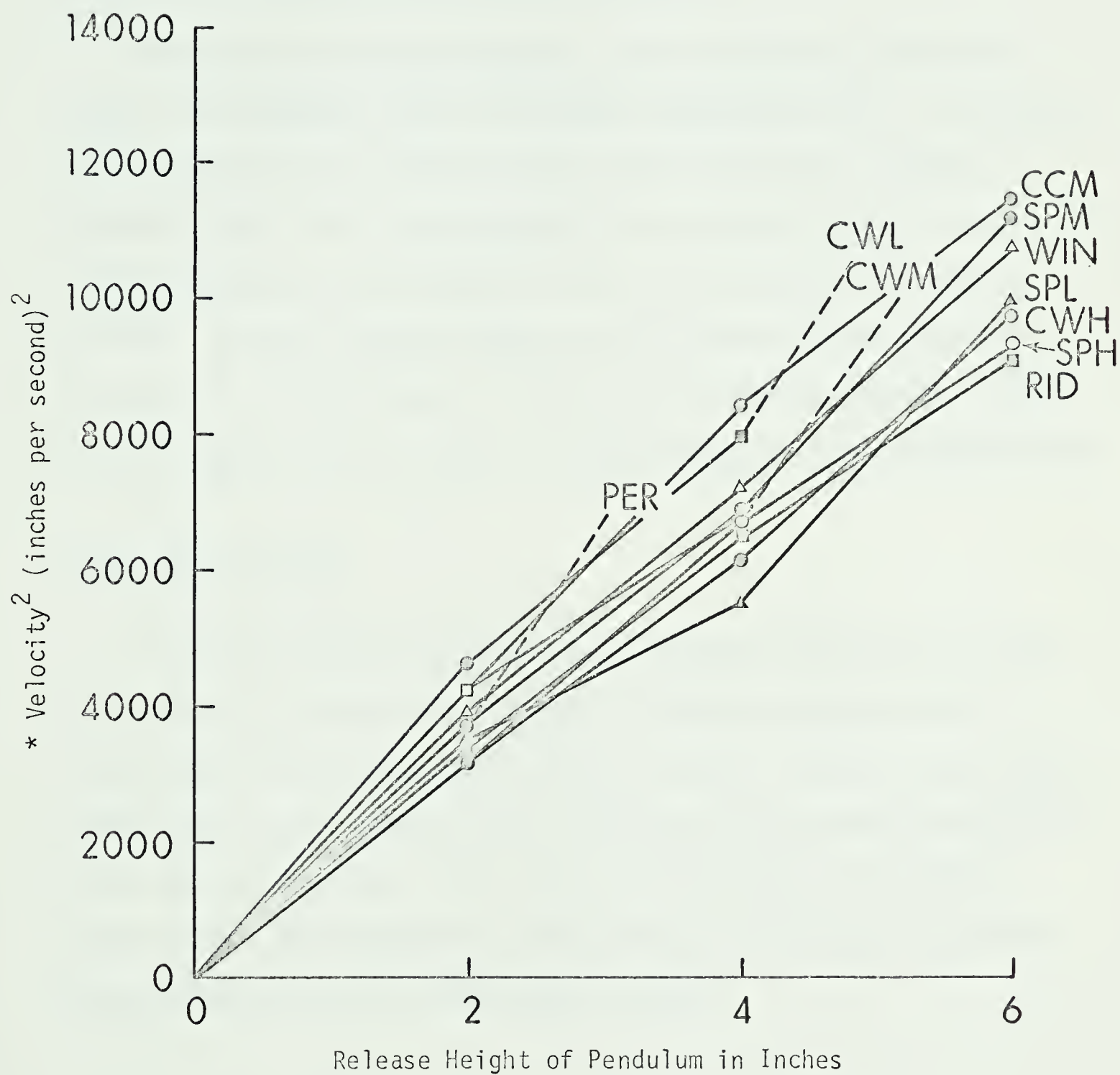
If the highest velocity of the pendulum represents the severest test condition, then the superior helmets at the back position are the RID, SPH, and CWH. Inferior helmets at the back position, due to large overshoots and high peak accelerations developed over a short period of



* If the Mass is Constant then Kinetic Energy is Proportional to Velocity Squared.

FIGURE 10

THE EFFECT OF THREE RELEASE HEIGHTS OF THE PENDULUM
ON VELOCITY SQUARED FOR TEN HELMETS AT THE FRONT
POSITION



* If the Mass is Constant then Kinetic Energy is Proportional to Velocity Squared.

FIGURE 11

THE EFFECT OF THREE RELEASE HEIGHTS OF THE PENDULUM ON
VELOCITY SQUARED FOR TEN HELMETS AT THE BACK
POSITION

time, are the PER, CWL, and CWM.

Comparing Peak Acceleration and Kinetic Energy

In comparing the two parameters, peak acceleration and kinetic energy, there appears to be a difference between the two. In analyzing peak acceleration and kinetic energy transmitted to the headform, it becomes evident that in both parameters the superior helmets at the front position are the RID and CWH and at the back position the RID and SPH. The same inferior helmets for the front and back positions are found in both parameters. However, the difference between helmets does not appear to be as great in kinetic energy as in peak acceleration.

Statistical Analysis

A two-way analysis of variance with repeated measures on two factors, helmets and positions, was used to determine whether or not significant differences between helmets existed. A total of nine blows, three blows at each velocity, were delivered to each helmet at both the front and back positions. The results of the analysis of variance using the raw peak acceleration scores for all nine blows to each helmet at each position are summarized in Table V.

TABLE V
ANALYSIS OF VARIANCE-SUMMARY
PEAK G's FOR ALL BLOWS

Source	Sums of Squares	df	Mean Squares	F
Helmets	6,464.63	9	718.29	4.71*
Positions	372.62	1	372.62	2.44
Helmets x Positions	6,354.94	9	706.10	4.63*
Error	24,413.31	160	152.58	
Total	37,605.50	179		

* significant at .01 level.

Analysis of variance yielded significant F values for helmets, and helmets by position interaction. The significant F value for helmets indicates that a significant difference between helmets exists. The non-significant F value for positions indicates that no significant difference exists between the front and back positions. However, the significant F value for helmets by positions interaction indicates that helmets vary according to the position tested. This is verified by examining the peak g values attained by the SPL helmet. The helmet attained a high peak value when tested at the front position but the g value was much lower at the back position. Similarly, the same characteristic is demonstrated by the CWH and CWL helmets. These helmets had low g's at the front position but high g's at the back position.

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CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purpose of this study was to evaluate ten different commercial hockey helmets for their ability to absorb energy at selected sites from standardized blows. A sub-problem was to determine changes, if any, in the ability of helmets to absorb energy when the velocity of the blow is varied.

The testing equipment consisted of a pendulum impact arrangement, a wooden headform, and recording instruments. The hockey helmets were fitted onto the headform and three different velocities of the pendulum were used to deliver the blows. A piezoelectric accelerometer, mounted in the head at a point diametrically opposite the point of impact, was used to detect impact effects. The technique was to have the accelerometer's signals amplified and imposed on the graticule of a cathode ray storage oscilloscope. The stored images, which were acceleration-time curves, were then photographed for permanent records. Two measurements, peak acceleration and kinetic energy, were calculated from the photographed recordings and used to evaluate the helmets.

A helmet displayed excellent energy absorbing ability if a low order of acceleration was developed over a broad base in terms of time. A helmet displayed poor energy absorbing ability if high accelerations were developed over a short period of time.

Conclusions

The following conclusions are warranted as a result of the analysis of the data in this study.

1. A significant difference between the energy absorbing qualities of the ten helmets was found to exist.
2. Hockey helmets vary according to the position tested.
3. Different energy absorbing responses by hockey helmets are obtained when the velocity of the blow is varied.
4. The magnitude of energy transmitted to the headform is reduced considerably when the moulds of helmets are not in direct contact with the headform.
5. In general, the helmet that developed the lowest order of acceleration and dissipated the resultant energy over a broad base in terms of time was one that is constructed from strong plastic and utilizes a suspension system similar to that found in a football helmet.
6. The testing technique yields a valid comparative evaluation of hockey helmets.
7. The majority of hockey helmets utilize multi-piece shells. It would appear at this time that the single unit construction is the superior helmet design.
8. The results show a fair divergence between helmets when compared on the basis of peak acceleration. This divergence decreases when helmets are compared on the basis of kinetic energy transmitted to the headform.

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APPENDIX A
HOCKEY HELMETS USED

HELMETS EMPLOYED IN THE STUDY

<u>CODE</u>	<u>MANUFACTURER</u>	<u>MODEL</u>	<u>LISTED RETAIL PRICE</u>
SPL	Spalding	HH5	\$ 4.90
SPM	Spalding	HH2	\$ 9.30
SPH	Spalding	HH0	\$18.50
CWL	Cooper	SK10	\$ 5.75
CWM	Cooper	SK12	\$ 9.75
CWH	Cooper	SK20	\$19.50
CCM	CCM	1 model	\$ 5.50
WIN	Winwell		\$10.00
			\$ 9.00
RID	Riddell	H-110	\$20.00
PER	Perdix	1 model	\$ 7.00

DESCRIPTION OF HELMETS

SPL

weight: 10 ounces
mould: one-eighth inch plastic (polyethylene)
exterior: no covering
interior: three-sixteenth inch plastic foam
fit: two-piece adjustable

SPM

weight: 11.5 ounces
mould: one-eighth plastic (polyethylene)
exterior: no covering
interior: one-quarter inch plastic foam, leather lined
fit: two-piece adjustable

SPH

weight: 15 ounces
mould: one-eighth inch plastic (polyethylene)
exterior: one-eighth inch plastic foam, leather lined
fit: two-piece adjustable

CWL

weight: 9.5 ounces
mould: one-eighth inch plastic (polyethylene)
exterior: no covering
interior: three-sixteenth inch plastic foam
fit: three-piece adjustable

CWM

weight: 12 ounces
mould: one-eighth inch plastic (polyethylene)
exterior: no covering
interior: three-sixteenth inch rubber like substance
fit: three-piece adjustable

CWH

weight: 15 ounces
mould: one-eighth plastic (polyethylene)
exterior: one-sixteenth inch rubber like substance, leather lined
interior: three-sixteenth inch rubber like substance, leather lined
fit: three-piece adjustable

CCM

weight: 10 ounces
mould: one-eighth inch plastic
exterior: no covering
interior: one-quarter inch plastic foam, extra foam for front, back, and sides available
fit: two-piece adjustable

WIN

weight: 11 ounces
mould: one-eighth inch plastic
exterior: no covering
interior: one-quarter inch rubber like substance at the top front, back, and sides
fit: two-piece adjustable

RID

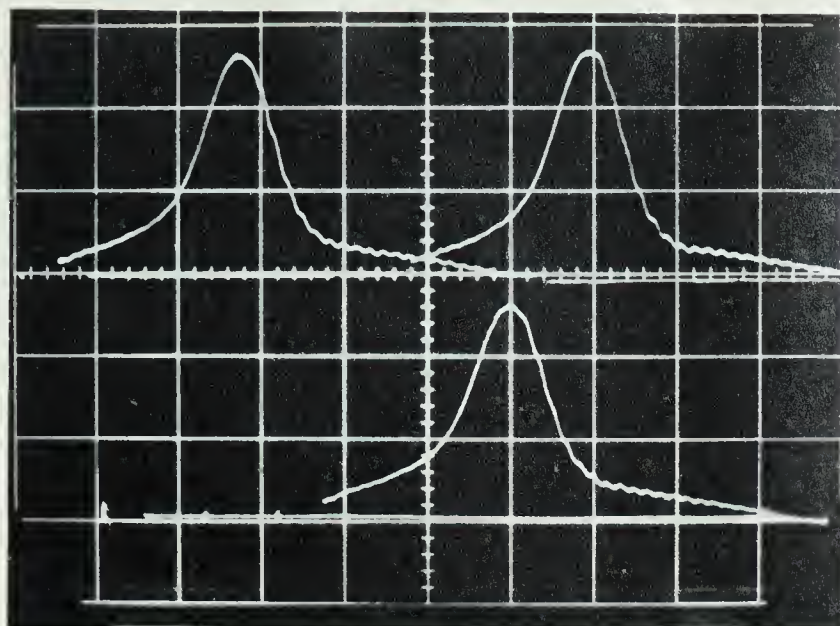
weight: 22 ounces
mould: three-sixteenth inch strong plastic
exterior: no covering
interior: football helmet suspension system
fit: one-piece non-adjustable

PER

weight: 8 ounces
mould: one-sixteenth inch plastic, easily compressed
interior: modified suspension, rubber like patches at front, back, and sides
exterior: no covering
fit: two-piece adjustable

APPENDIX B

VARIOUS WAVE-FORMS



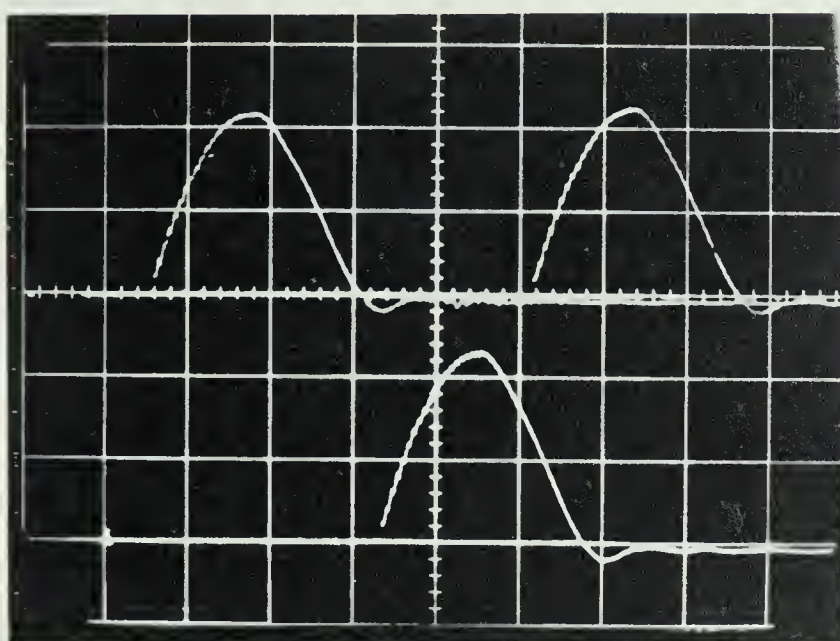
Helmet: PER

Position: Back

Velocity: 39 ft./sec.

Vertical: 1 volt/cm.

Horizontal: 2 ms./cm.



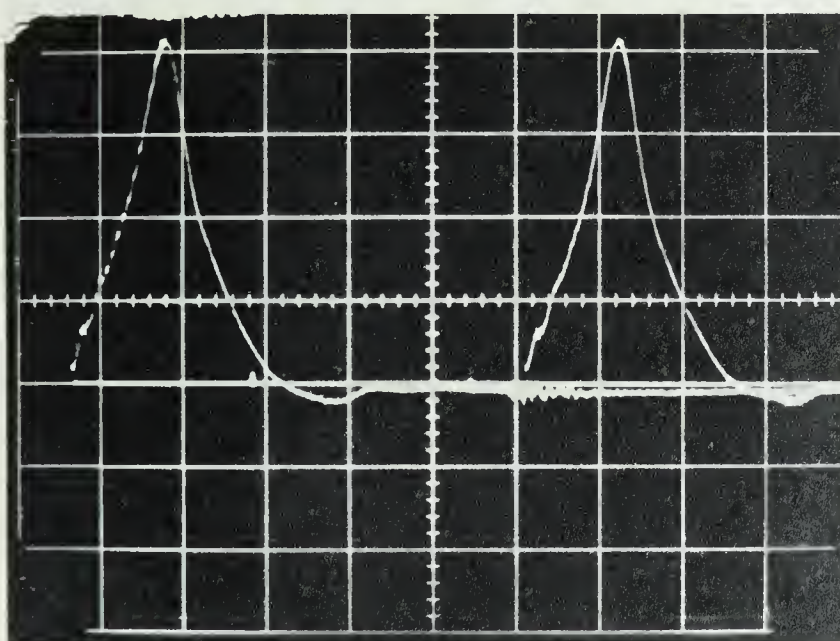
Helmet: CWL

Position: Front

Velocity: 39 ft./sec.

Vertical: .5 volt/cm.

Horizontal: 5 ms./cm.



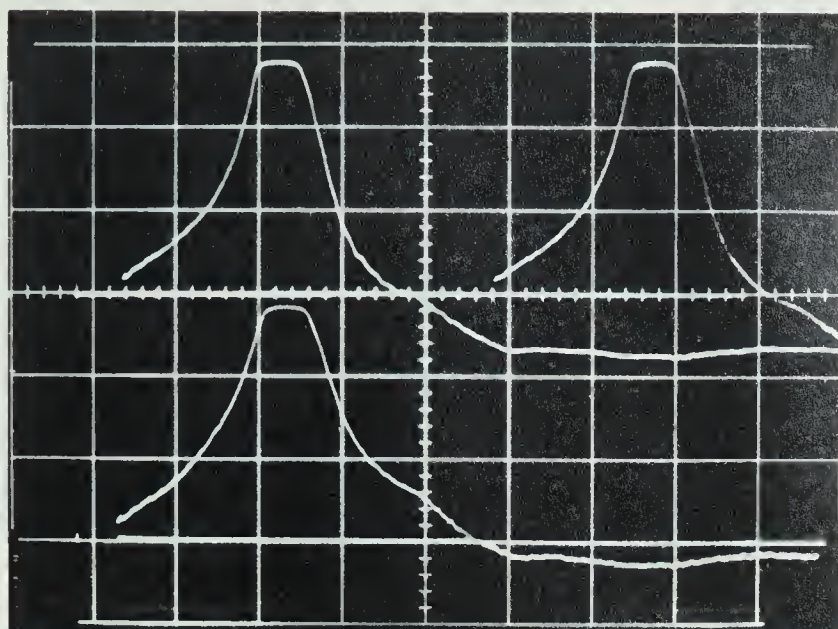
Helmet: PER

Position: Front

Velocity: 56 ft./sec.

Vertical: .5 volt/cm.

Horizontal: 5 ms./cm.



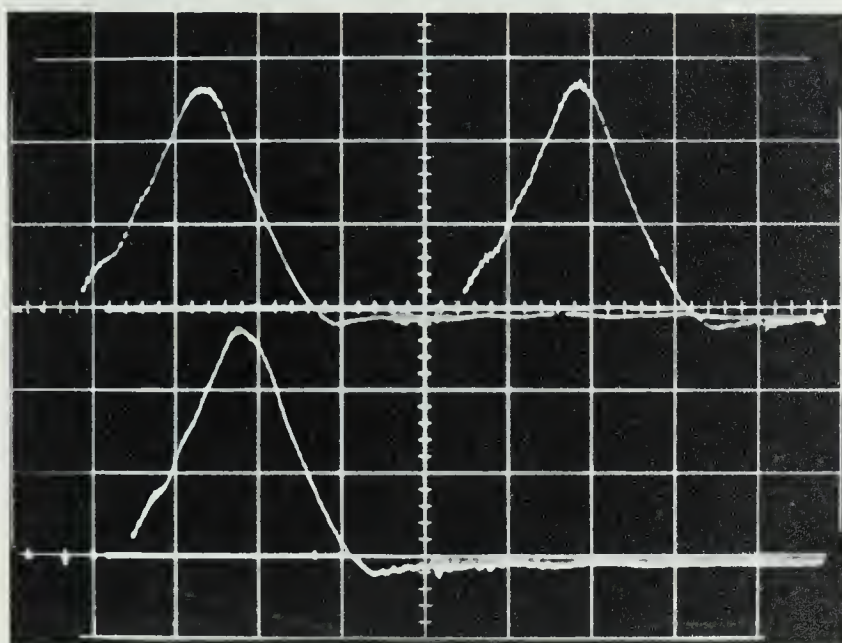
Helmet: SPL

Position: Front

Velocity: 56 ft./sec.

Vertical: 1 volt/cm.

Horizontal: 2 ms./cm.



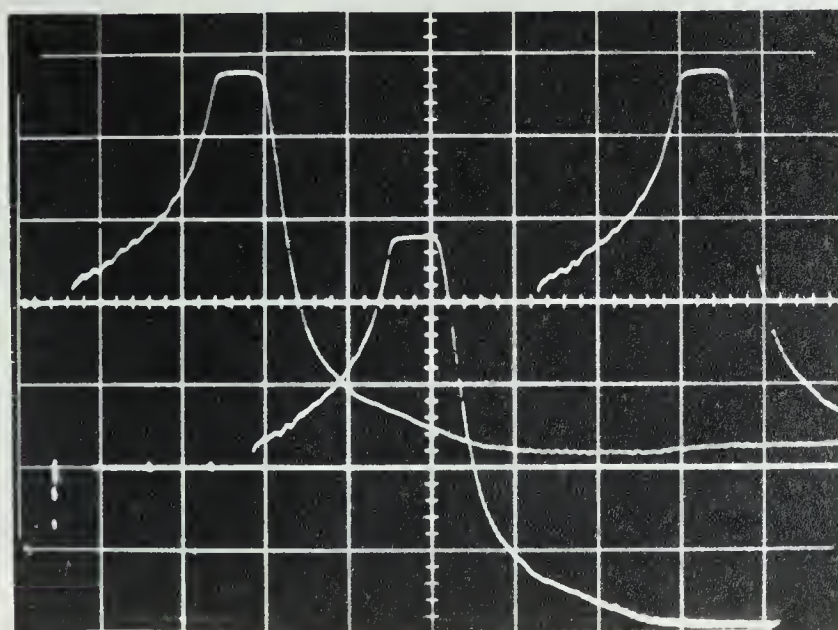
Helmet: SPL

Position: Back

Velocity: 56 ft./sec.

Vertical: .5 volt/cm.

Horizontal: 5 ms./cm.



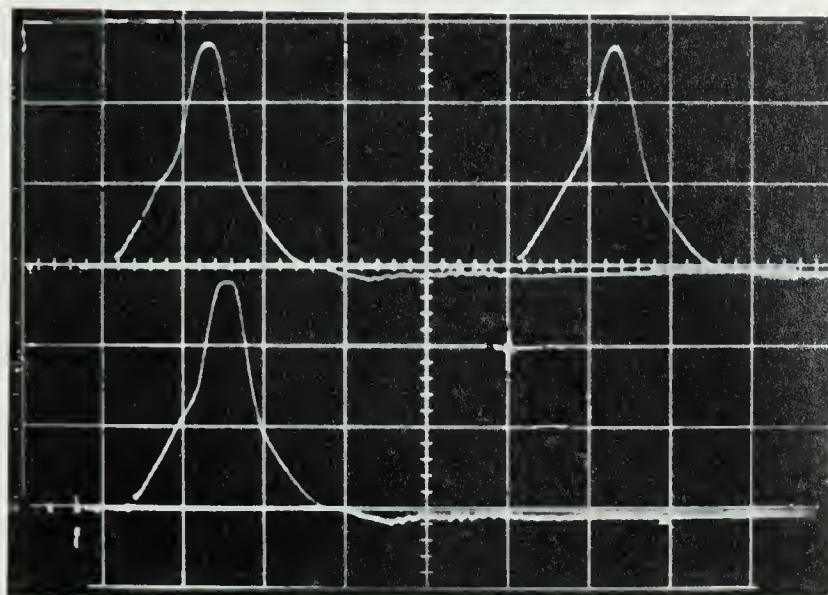
Helmet: PER

Position: Front

Velocity: 68 ft./sec.

Vertical: 1 volt/cm.

Horizontal: 2 ms./cm.



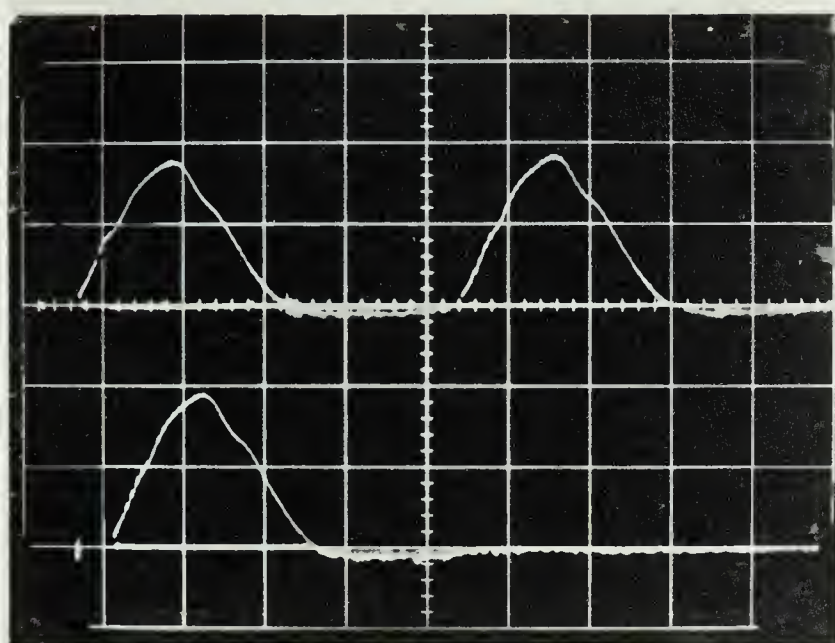
Helmet: WIN

Position: Front

Velocity: 68 ft./sec.

Vertical: 1 volt/cm.

Horizontal: 5 ms./cm.



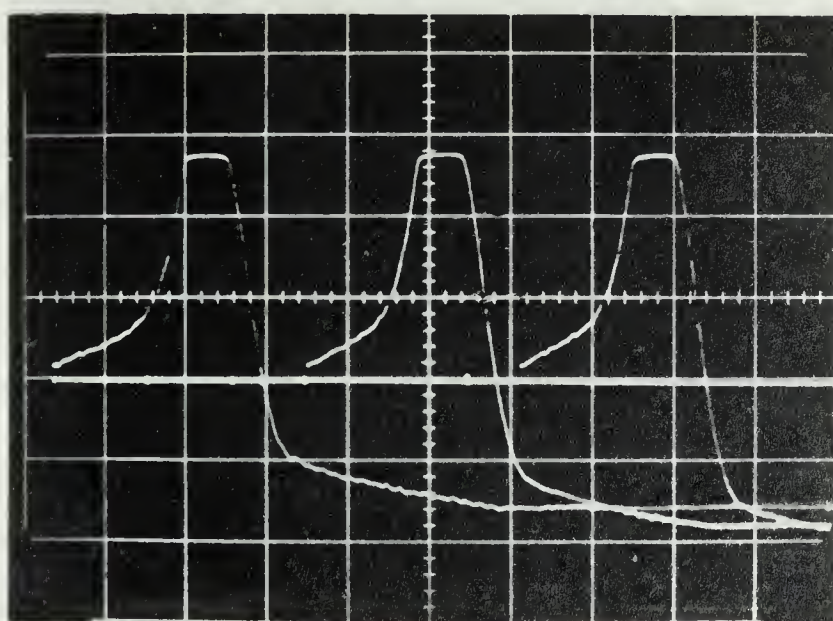
Helmet: SPH

Position: Back

Velocity: 68 ft./sec.

Vertical: 1 volt/cm.

Horizontal: 5 ms./cm.



Helmet: PER

Position: Back

Velocity: 56 ft./sec.

Vertical: 1 volt/cm.

Horizontal: 2 ms./cm.

APPENDIX C
FORMULAS

FORMULA FOR THE VELOCITY OF THE PENDULUM

$$V = \sqrt{2gh}$$

Where:

V = Velocity of the Pendulum in Inches
Per Second

g = Constant of 386 Inches Per Second-
Second

h = The Vertical Height in Inches from
which the Pendulum was Released

CALCULATION OF PEAK ACCELERATION

$$PA = \frac{P \times K \times V \times 1000}{48.8}$$

Where:

PA = Peak Acceleration in G's

P = Height of the Peak in Centimeters

K = Constant of 1.075 for the Scale Effect
between the Graticule of the Oscillo-
scope and Polaroid Film

V = Voltage or Vertical Sensitivity on the
Oscilloscope in Volts

1000 = Constant to Convert Volts into Millivolts

48.8 = Sensitivity of the Accelerometer 48.8 mV/G

* CALCULATION OF VELOCITY SQUARED

$$V^2 = \left[\frac{A \times K_1 \times K_2 \times gV \times T}{48.8 \text{ mV/G}} \right]^2$$

Where:

$$V^2 = (\text{Inches Per Second})^2$$

A = Area Under Acceleration-Time Curve
in Square Inches

K₁ = Constant of 6.45 to Convert the Area
into Square Centimeters

K₂ = Constant of 1.16 for the Scale Effect
between the Graticule of the Oscillo-
scope and Polaroid Film

g = Constant of 386 Inches Per Second Per Second

V = Voltage or Vertical Sensitivity Setting
on the Oscilloscope in Volts

T = Time or Horizontal Sensitivity Setting
on the Oscilloscope in Milliseconds

48.8 = Sensitivity of the Accelerometer in mV/G

- * If the mass for all helmets is considered constant then kinetic energy is proportional to the velocity squared.

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